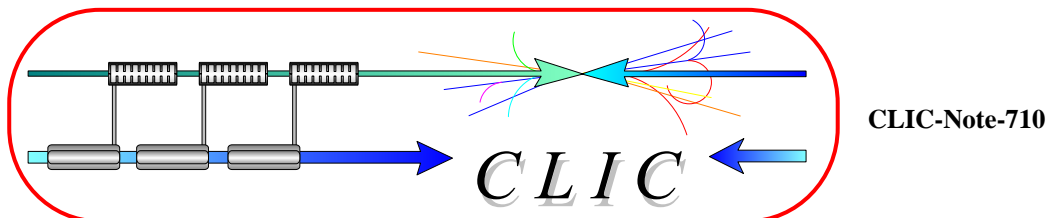


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BEAM-BASED DIAGNOSTICS OF RF-BREAKDOWN IN THE TWO-BEAM TEST-STAND IN CTF3

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Abstract

The general outline of a beam-based diagnostic method of RF-breakdown, using BPMs, at the two-beam test-stand in CTF3 is discussed. The basic components of the set-up and their functions in the diagnostic are described. Estimations of the expected error in the measured parameters are performed.

*Geneva, Switzerland
(27 August 2007)*

1 Introduction

In order to test the key features of the CLIC [1] accelerating scheme a facility called the "CLIC Test Facility", CTF3, is in construction at CERN. The main goal of this facility is to give proof-of-principle of all the main features of CLIC by 2010. CTF3 is constructed in phases, and an additional building, the CLEX building, is currently under construction in the CTF3 complex. This building will house the two-beam test-stand (TBTS), which will test the power generation and the power transfer with "power extraction and transfer structures" (PETS) to accelerating structures, operating on a beam with nominal CLIC parameters. A recent overview of CTF3 can be found in [2].

Uppsala University is part of the CTF3 collaboration since 2006, with funding from the Swedish research council and the Wallenberg foundation. Uppsala's role in the CTF3/CLIC collaboration is to develop, design, produce and install the beam transfer lines needed for the two-beam test-stand. TBTS is in the remainder of this paper to be understood as both the test-stand with PETS and accelerating structures, as well as the surrounding infrastructure.

One of the major efforts in the current high-gradient set-up in CTF3 is to understand, and if possible, limit the effect of so-called "RF-breakdown". The theory behind this phenomena is not well understood, and even though much effort has been put into the subject [3], much work is still left to be done. A review of the current high-gradient tests performed at CTF3 can be found in [4].

The purpose of the TBTS is not only to provide infrastructure for the accelerating structures and PETS, but also to perform analysis of how RF-breakdown affects the beam. This is done by observing the beam centroid position with BPMs.

RF-breakdown in the PETS and accelerating structures will affect the stability and reliability of operation. The reasons for this are both a direct change in the beam angle and energy due to the RF-breakdown kick, as well as wakefield-generated transverse instabilities. Depending on the magnitude of the kick, this will reduce the luminosity at the interaction point, and will in the case of high magnitude kicks lead to beam dumping in the collimators and other equipment in the misdirected beam path, with poten-

tially extensive damage as result. Replacement of damaged equipment will cause extended down-time for the whole machine, and thus greatly reduced integrated luminosity.

These potential problems warrant a careful investigation of the magnitude of the kick caused by RF-breakdown. In the remainder of this note we discuss the accuracy to which we can determine this magnitude by directly observing the beam with BPMs.

The magnitudes of kick which can be observed with the method outlined in this paper depend both on the geometry of the set-up and the accuracy of the BPMs used. Simulations and observations of the magnitude of the kick at the accelerating cavities at NLC [5] have yielded kicks with a magnitude of about 3-100 keV. In the case of the CTF3 150 MeV beam, this kick corresponds to a change in beam angle of about $20 \mu\text{rad}$ - 0.5 mrad .

2 Definitions, notations and abbreviation

The *beam state* at the longitudinal location a is defined by a three-entry vector, \mathbf{x}^a :

$$\mathbf{x}^a = \begin{bmatrix} x^a \\ x'^a \\ \delta^a \end{bmatrix}, \quad (1)$$

where x^a is the horizontal offset of the center-of-mass of the beam, x'^a is the the horizontal angle of the center-of-mass and δ^a is the relative energy deviation. In the case of high-energy, highly relativistic electrons, this notation coincides with the one used in the program MAD-X [6].

Subscript is to be understood as vector entry index, and superscript as longitudinal position. Thus x_i^a is to be taken as the i :th entry of the vector \mathbf{x} at the longitudinal position a (e.g. $x_1^a = x^a$, $x_2^a = x'^a$ and $x_3^a = \delta^a$).

The transfer matrix from point a to point b is given by \mathbf{M}^{ba} , which is a 3×3 matrix. The state of the beam at location b is given by multiplying the transfer matrix from point a to b with the vector describing the state of the vector at a :

$$\mathbf{x}^b = \mathbf{M}^{ba} \mathbf{x}^a. \quad (2)$$

The abbreviation BPM will be used extensively for Beam Position Monitor. A description of the BPMs which will be used in the two-beam test-stand can be found in [7].

3 Experimental set-up

The experiment consists of 5 BPMs, one dipole and two chicanes (see figure 1). This set-up will be used with identical geometry for both the drive-beam, measuring breakdown-kicks in the PETS, and for the probe-beam, measuring breakdown-kicks in the accelerating structures.

The BPMs will be used to make an estimation of the kick parameters. In principle, the first two BPMs allow the two unknown parameters of the incoming beam to be determined, namely incoming beam offset, x^1 , and incoming beam angle, x'^1 . BPM3 and BPM4 will allow to determine the breakdown kick change in angle, θ .

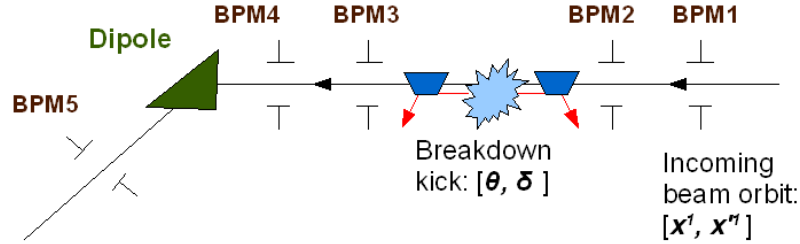


Figure 1: General set-up of the experiment

The dipole will introduce the dispersion needed to resolve the change in relative beam energy, δ , added by the kick. The bending angle of the dipole is 22.75° . The geometry has been modeled in MAD-X, which provides an easy and quick way to extract all the transfer matrices¹. A quick overview of the relevant element and their placement is displayed in table 1.

¹The accelerating structure is inserted as a drift, thus neglecting the focusing properties of the accelerating structure. This is a valid approximation since the equivalent radial displacement is proportional to both the radial offset (which is small in the accelerating structures) and inversely proportional to γ^3 (which is high) [8]

Element	Length of element [m]	Longitudinal position relative BPM1 [m]
BPM1	0.168	0
BPM2	0.168	1.6
BPM3	0.168	4.0
BPM4	0.168	6.1
DIPOLE	0.479	8.8
BPM5	0.168	9.9

Table 1: The length and longitudinal position of the elements used in the experiment.

Each of the two chicanes (blue trapezoids in figure 1) is a pair of weak dipole magnets. The reason for the chicanes is to prevent breakdown-currents to "blind" the BPMs closest to the breakdown, and will diverge the low-energy breakdown electrons, while leaving the high-energy beam electrons largely unaffected. The chicanes were included in the set-up after the problem with breakdown currents were pointed out by V.Dolgashev. Their specific design will be addressed in an upcoming note.

4 Least square estimation of the kick

If all the transfer matrices are known, it is straightforward to perform a least-square fit of the kick parameters. In this section, a method for performing a least-square estimation of the kick parameters for a given set of BPM readout is outlined.

Four parameters can be fit to the readout of the BPMs: the incoming beam offset, x^1 , the incoming beam angle, x'^1 , the change in beam angle due to the kick, θ , and the change in relative energy of the beam due to the kick, δ .

The beam-state, and thus the read-out of all of the BPM will depend on the first two of these parameters, (beam offset, x^1 , and beam angle, x'^1). The beam state at BPM3-5 will also depend on what happens with the beam during the breakdown, or in other words the *breakdown kick* (represented by kick change in beam angle, θ , and kick change in relative beam energy, δ).

BPM1 and BPM2 will thus allow for determining the incoming beam angle and offset, and BPM3, BPM4 and BPM5 will allow for determining the kick parameters θ and δ .

The read-out of the n :th BPM is a read-out of the beam offset at the longitudinal location of that BPM:

$$x_1^n = x^n. \quad (3)$$

If we define the initial state of the beam as the state of the beam at BPM1, the initial beam state becomes, in vector notation:

$$\mathbf{x}^1 = \begin{bmatrix} x^1 \\ x'^1 \\ 0 \end{bmatrix}. \quad (4)$$

The beam is propagated from BPM1 to BPM2 with the transfer matrix from BPM1 to BPM2, \mathbf{M}^{21} . The state of the beam at BPM2 will thus be \mathbf{x}^2 :

$$\mathbf{x}^2 = \begin{bmatrix} x^2 \\ x'^2 \\ \delta^2 \end{bmatrix} = \mathbf{M}^{21} \mathbf{x}^1 = \begin{bmatrix} M_{11}^{21} & M_{12}^{21} & M_{13}^{21} \\ M_{21}^{21} & M_{22}^{21} & M_{23}^{21} \\ M_{31}^{21} & M_{32}^{21} & M_{33}^{21} \end{bmatrix} \begin{bmatrix} x^1 \\ x'^1 \\ 0 \end{bmatrix}. \quad (5)$$

The first entry of this vector is the beam offset at BPM2, x^2 :

$$x_1^2 = x^2 = M_{11}^{21} x^1 + M_{12}^{21} x'^1. \quad (6)$$

The beam state at BPM3 will be determined not only by the incoming beam parameter, but also by the kick. The kick might change the beam energy, δ , and the beam angle, θ . The kick is represented by the kick vector, \mathbf{k} :

$$\mathbf{k} = \begin{bmatrix} 0 \\ \theta \\ \delta \end{bmatrix}. \quad (7)$$

The beam state at BPM3 is given by \mathbf{x}^3 , which depends both on the incoming beam parameters and the kick parameters:

$$\begin{aligned}\mathbf{x}^3 &= \mathbf{M}^{31}\mathbf{x}^1 + \mathbf{M}^{K3}\mathbf{k} \\ &= \begin{bmatrix} M_{11}^{31} & M_{12}^{31} & M_{13}^{31} \\ M_{21}^{31} & M_{22}^{31} & M_{23}^{31} \\ M_{31}^{31} & M_{32}^{31} & M_{33}^{31} \end{bmatrix} \begin{bmatrix} x^1 \\ x'^1 \\ 0 \end{bmatrix} \\ &\quad + \begin{bmatrix} M_{11}^{3K} & M_{12}^{3K} & M_{13}^{3K} \\ M_{21}^{3K} & M_{22}^{3K} & M_{23}^{3K} \\ M_{31}^{3K} & M_{32}^{3K} & M_{33}^{3K} \end{bmatrix} \begin{bmatrix} 0 \\ \theta \\ \delta \end{bmatrix}.\end{aligned}\tag{8}$$

As before, the first entry of the vector \mathbf{x}^3 is the beam offset at the third BPM:

$$x_1^3 = x^3 = M_{11}^{31}x^1 + M_{12}^{31}x'^1 + M_{12}^{3K}\theta + M_{13}^{3K}\delta.\tag{9}$$

The beam offset at BPM4 and BPM5 is obtained in a similar manner:

$$x_1^4 = x^4 = M_{11}^{41}x^1 + M_{12}^{41}x'^1 + M_{12}^{4K}\theta + M_{13}^{4K}\delta,\tag{10}$$

$$x_1^5 = x^5 = M_{11}^{51}x^1 + M_{12}^{51}x'^1 + M_{12}^{5K}\theta + M_{13}^{5K}\delta.\tag{11}$$

We can summarize the beam offset at BPM1-5, equation (4), (6), (9), (10) and (11), in matrix form:

$$\begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ x^4 \\ x^5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ M_{11}^{21} & M_{12}^{21} & 0 & 0 \\ M_{11}^{31} & M_{12}^{31} & M_{12}^{3K} & 0 \\ M_{11}^{41} & M_{12}^{41} & M_{12}^{4K} & 0 \\ M_{11}^{51} & M_{12}^{51} & M_{12}^{5K} & M_{13}^{5K} \end{bmatrix} \begin{bmatrix} x^1 \\ x'^1 \\ \theta \\ \delta \end{bmatrix} = \mathbf{A} \begin{bmatrix} x^1 \\ x'^1 \\ \theta \\ \delta \end{bmatrix}.\tag{12}$$

Note that only the read-out of BPM5 will depend on the kick change in relative beam energy δ , since this is the only BPM placed downstream of the dipole, which means that $M_{13}^{3K} = M_{13}^{4K} = 0$ and $M_{13}^{5K} \neq 0$. Equation 12 is an over-determined equation system (four unknown parameters and five

equations), and can be solved in the least-square sense. The least-square estimation of the unknown parameters is given by [9]:

$$\begin{bmatrix} x^1 \\ x'^1 \\ \theta \\ \delta \end{bmatrix} \approx (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ x^4 \\ x^5 \end{bmatrix}, \quad (13)$$

where \mathbf{A} is defined in equation 12. Here \approx is used instead of $=$ since a over-determined equation system with a non-exact readout is generally not exactly solvable due to non-accurate readout.

The LHS of equation 13 is the estimation of the unknown parameters, and the RHS consists of transfer matrix elements as well as the readout of BPM1-5, all of which is given when performing the experiment.

Note that the expression $(\mathbf{A}^T \mathbf{A})^{-1}$ can be used to estimate the error in the least-square fit due to inaccurate in-data (BPM readout). This is done in the following section.

5 Error estimation

The BPMs have a limited accuracy in the readout. Following [9] further, we can estimate the accuracy of the experiment by using standard linear algebra methods. If the accuracy, σ , is equally large in each BPM we can estimate the error, Δ_k , in the least-square fit of each parameter due to inexact BPMs. This is done by introducing the covariance matrix, \mathbf{C} :

$$\mathbf{C} = (\mathbf{A}^T \mathbf{A})^{-1} \sigma^2, \quad (14)$$

where \mathbf{C} is a 4×4 matrix. The error in the estimation of each fit parameter, due to inaccuracy in the BPMs Δ_k , can now be found:

$$\begin{bmatrix} \Delta_{x^1} \\ \Delta_{x'^1} \\ \Delta_{\theta} \\ \Delta_{\delta} \end{bmatrix} = \begin{bmatrix} \sqrt{C_{11}} \\ \sqrt{C_{22}} \\ \sqrt{C_{33}} \\ \sqrt{C_{44}} \end{bmatrix}. \quad (15)$$

A summary of the expected error in the estimations can be found in section 8.

6 Longitudinal position of the breakdown

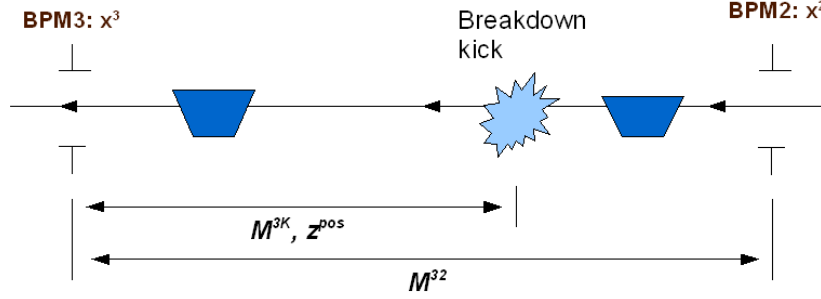


Figure 2: Longitudinal position of the kick.

The method outlined above is valid when the distance, and thus the transfer matrix, between breakdown and BPM3, \mathbf{M}^{3K} is known. This is not generally the case, since breakdown occurs at different locations in the accelerating structures, with a higher probability where the surface electric field is higher. In the following two subsections two different methods for estimating the longitudinal kick position, z^{pos} , and the corresponding transfer matrix \mathbf{M}^{3K} , of the breakdown is outlined.

6.1 Longitudinal position of the breakdown (1)

One way of performing a fit of the longitudinal position z^{pos} is to divide the distance between BPM2 and BPM3 into N pieces, and construct a transfer matrix $\mathbf{M}^{3K,i}$ for each distance $i = [0...N]$ between the kick and BPM3. $i = 0$ corresponds to the same longitudinal position as BPM2, and $i = N$ to the position of BPM3. Constructing the transfer matrices for each i is trivial, since the space between BPM2 and BPM3 is just a driftspace. By performing a least square fit for each position $i = [1...N]$ we will get a total of N sets of estimated parameters, $[x^1, x'^1, \theta, \delta]$.

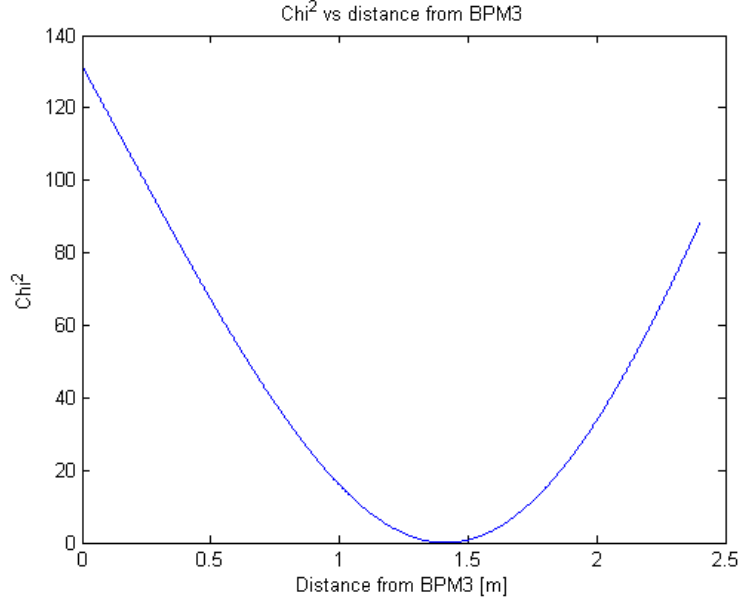


Figure 3: Example of error χ^2 vs position i plot.

For each set of parameters, we can calculate the difference between the BPM readout and the position given by inserting the set of estimated parameters into equation (12). We call this difference χ , and we can plot χ^2 as a function of position, i . This will generate plots, e.g. as seen in fig 3. The χ^2 used in this figure is calculated by degrees-of-freedom (ie χ^2 is divided by number of fit parameters, which is 4 in this case).

An estimation of the error in longitudinal position due to the limited accuracy in BPMs can be made by calculating the longitudinal distance between the two points where χ^2 is equal to one [9].

6.2 Longitudinal position of the breakdown (2)

A different possibility to determine the parameters of the kick is to introduce another parameter, x^K , which is the distance between the kick and BPM2, z^{pos} , multiplied by the kick change in angle, θ (see also figure 4):

$$x^K = z^{pos}\theta. \quad (16)$$

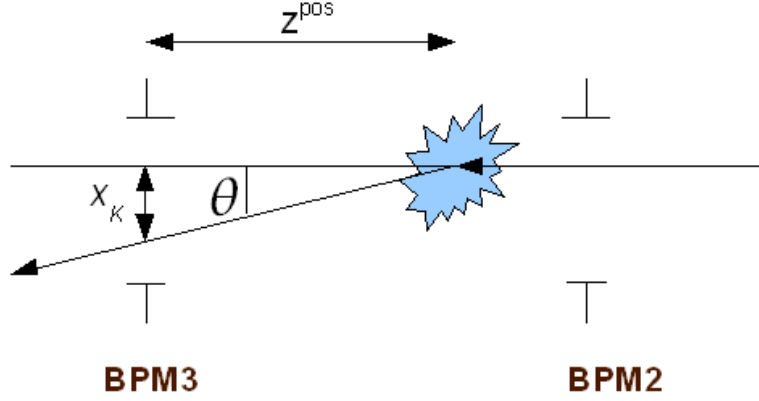


Figure 4: Illustration of the extra variable x^K .

Introducing the parameter x^K defined above, and following the method in section 4, we arrive at an equation, similar to equation 12, which again defines a system of equations:

$$\begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ x^4 \\ x^5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ M_{11}^{21} & M_{12}^{21} & 0 & 0 & 0 \\ M_{11}^{31} & M_{12}^{31} & 1 & 0 & 0 \\ M_{11}^{41} & M_{12}^{41} & M_{11}^{43} & M_{12}^{43} & 0 \\ M_{11}^{51} & M_{12}^{51} & M_{11}^{53} & M_{12}^{53} & M_{13}^{53} \end{bmatrix} \begin{bmatrix} x^1 \\ x'^1 \\ x^K \\ \theta \\ \delta \end{bmatrix} = \mathbf{B} \begin{bmatrix} x^1 \\ x'^1 \\ x^K \\ \theta \\ \delta \end{bmatrix}, \quad (17)$$

where the kick now can be interpreted as a change in relative energy, δ , a change in beam angle, θ and a instantaneous change in beam offset, x^K , all applied just before BPM3. The least-square estimation of beam and kick parameters is now given by:

$$\begin{bmatrix} x^1 \\ x'^1 \\ x^K \\ \theta \\ \delta \end{bmatrix} \approx (\mathbf{B}^T \mathbf{B})^{-1} \mathbf{B}^T \begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ x^4 \\ x^5 \end{bmatrix}. \quad (18)$$

Since we not have an over-determined systems of equations, \mathbf{B} is square, and equation 18 is equal to the inverse of \mathbf{B} . The estimation of the longitudinal position of the breakdown, z^{pos} , can now be found as:

$$z^{pos} = x^K / \theta. \quad (19)$$

The error bars of the fit parameters can be found by the use of the covariance matrix, \mathbf{D} , introduced in the same manner as in section 5 :

$$\mathbf{D} = (\mathbf{B}^T \mathbf{B})^{-1} \sigma^2. \quad (20)$$

The error bars of the fit parameters in this case are given by:

$$\begin{bmatrix} \Delta_{x^1} \\ \Delta_{x'^1} \\ \Delta_{x^K} \\ \Delta_{\theta} \\ \Delta_{\delta} \end{bmatrix} = \begin{bmatrix} \sqrt{D_{11}} \\ \sqrt{D_{22}} \\ \sqrt{D_{33}} \\ \sqrt{D_{44}} \\ \sqrt{D_{55}} \end{bmatrix}. \quad (21)$$

The error bar, $\Delta_{z^{pos}}$, of the longitudinal position, z^{pos} , can be found by propagating the old covariance matrix \mathbf{D} to a new one, \mathbf{E} , which relates to the new parameter z^{pos} [9]. This is done by introducing the matrix \mathbf{J} :

$$\mathbf{J} = \begin{bmatrix} \frac{\partial z^{pos}}{\partial x^1} & \frac{\partial z^{pos}}{\partial x'^1} & \frac{\partial z^{pos}}{\partial x^K} & \frac{\partial z^{pos}}{\partial \theta} & \frac{\partial z^{pos}}{\partial \delta} \end{bmatrix}, \quad (22)$$

and then propagating the old covariance matrix, \mathbf{D} , to the new one, E :

$$E = \mathbf{J} \mathbf{D} \mathbf{J}^T. \quad (23)$$

In the general case, when introducing more than one parameter, E is a matrix, but since we only have one parameter, z^{pos} , E is in this case a scalar. The error bar, $\Delta_{z^{pos}}$, of the new parameter, z^{pos} , can now be found by:

$$\Delta_{z^{pos}}^2 = E. \quad (24)$$

Thus we obtain the following expression for the error in the longitudinal position, $\Delta_{z^{pos}}$:

$$\Delta_{z^{pos}}^2 = D_{33} \left(\frac{1}{\theta} \right)^2 - D_{34} \left(\frac{x^K}{\theta^2} \right) \left(\frac{1}{\theta} \right) - D_{43} \left(\frac{x^K}{\theta^2} \right) \left(\frac{1}{\theta} \right) + D_{44} \left(\frac{x^K}{\theta^2} \right)^2. \quad (25)$$

Note that the covariance matrix \mathbf{D} is symmetric, so $D_{34} = D_{43}$.

7 Expected error bars

By using the transfer matrices for the geometry described in section 3 and the theory from section 5 we can get an estimation on what the error will be in our estimation due to inexact indata (BPM readout). This has been done for both of the slightly different methods outlined in section 6.1 and 6.2, and the results for the inaccuracies Δ_k is displayed in table 2. The BPMs to be used in TBTS have an estimated uncertainty in the read-out, σ , of about 10 μm .

The error in incoming beam position, Δ_{x^1} , incoming beam angle, $\Delta_{x'^1}$, kick angle, Δ_θ , and relative energy change, Δ_δ , is given by the covariance matrix, equation 15. The covariance matrix is derived by the geometry of the set-up, represented by the matrices **A** and **B** in equation 12 and 17, and not on the numerical values of any of the fit parameters.

The longitudinal kick position, however, depends on both the geometry as well as the numerical values of the fit parameters (cf equation 25). Thus we need to do some estimations of the expected values of the fit parameters in order to make an estimation of the error bars of the longitudinal position. In table 2, the following numerical values was used for the fit parameters: $x^1 = 50 \mu\text{m}$, $x'^1 = 50 \mu\text{rad}$, $\theta = 100 \mu\text{rad}$, $\delta = 10^{-6}$ and $z^{pos} = \sqrt{2} \text{ m}$.

Estimated parameter	First method	Second method
Error in position, Δ_{x^1}	9.7 [μm]	10 [μm]
Error in angle, $\Delta_{x'^1}$	6.9 [μrad]	8.8 [μrad]
Error in kick angle, Δ_θ	11 [μrad]	11.1 [μrad]
Error in relative energy change from kick, Δ_δ	$32 \cdot 10^{-6}$	$39.6 \cdot 10^{-6}$
Error in x^K , Δ_{x^K}	NA	30.8 [μm]
Error in longitudinal position, $\Delta_{z^{pos}}$	0.50 [m]	0.25 [m]

Table 2: The length and longitudinal position of the elements used in the experiment.

When compared to the estimations made in section 1, one sees that even the lower limits of the kick angle, θ , (about 20 μrad), should be possible to resolve

with the given BPMs and set-up geometry. The resolution for longitudinal position is not good enough to determine in which cell in the accelerating structures the breakdown took place.

8 Conclusion and outlooks

A method to determine the parameters of RF-breakdown by using BPMs have been described, and the accuracy of these parameters have been estimated.

If the BPMs have a resolution of $10\text{ }\mu\text{m}$, we can expect to resolve the kick angle with an uncertainty of about $10\text{ }\mu\text{rad}$, and a relative energy deviation of about 4×10^{-5} . The longitudinal position can not be resolved with an accuracy better than several cm, which makes it impossible to determine in which cell in the accelerating structures the breakdown occurred.

The next step will be to determine in more detail what magnitudes we can expect of the estimated parameters. If the kick is too weak, the estimated parameters might "drown" in the error due to inexact BPMs, as discussed in section 7. In this case the BPMs could possibly be fine-tuned to a increased sensibility, or the placement of the BPMs along the beamline could be reconsidered. In general, more accuracy is gained the further away from the kick the downstream BPMs are placed.

A system which automatically acquires the data, and performs the analysis outlined in this paper will also be developed and integrated in the CTF3 software structure.

9 Acknowledgments

The author would like to thank V. Ziemann at Uppsala University for the effort put into this paper as supervisor and proof-reader, V. Dolgashev for pointing out the possible problem of dark-currents blinding the BPMs, S. Doeberl, W. Wuensch and A. Rodriguez, all at CERN, for introducing me to CTF3 and patiently answering my questions about accelerator physics.

Financial support from the Swedish Research Council and the Knut and Alice Wallenberg Foundation is gratefully acknowledged.

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